In response to the rules adopted in the First R&O, Siemens filed a petition for reconsideration requesting revisions to the existing UWB rules.[7] As part of its petition, Siemens also submitted a proposed measurement technique for measuring the emissions of pulsed FH vehicular radar systems.[8] The Commission addressed the Siemens Petition in its Memorandum Opinion and Order (MO&O) and Further Notice of Proposed Rulemaking (FNPRM) by denying the petition for reconsideration and by seeking advice from the public in the FNPRM.[9]

2. MEASUREMENT PLAN OBJECTIVES

The objectives of these measurements are to gain further insight into the proper techniques for measuring the emissions of devices employing pulsed FH modulation for compliance and use in compatibility studies. The measurements in this plan are to be performed by NTIA's Institute for Telecommunication Sciences (ITS) in conjunction with NTIA's Office of Spectrum Management (OSM).

3. APPROACH

NTIA believes that the emission spectrum characteristics of a pulsed FH transmitter can vary depending on the following system parameters pulse width (PW), pulse repetition frequency (PRF), frequency hopping bandwidth, frequency hopping pattern, number of frequency hopping channels, hopping channel frequency separation, and time length of the hopping sequence. There are two questions that will be addressed by these measurements First, what impact does varying the combinations of the pulsed FH system parameters have on the compliance measurements? Second, since the compliance measurements are performed in a narrow resolution bandwidth (e.g., 1 MHz) and the EESS sensor has a relatively wide bandwidth (e g., 400 MHz), can compliance measurements of the emissions be used in performing compatibility studies?[10]

In order to accomplish the objectives of the measurement plan, the following approach will be taken:

- Develop a prototype of a pulsed FH signal generator. The prototype will be capable of varying the pulsed FH system parameters as required to address the questions in the FNPRM.

- Perform measurements to verify the pulsed FH system parameters. These measurements include but are not limited to the: frequency range of hopping channels, frequency difference in hopping channels, number of hopping channels, hopping frequency characteristics (e.g., hopping pattern, length of sequence,

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[7] *Petition for Reconsideration of Siemens VDO Automotive AG*, ET Docket No 98-153

[8] *Id* at Appendix A

[9] *Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems*, Memorandum Opinion and Order and Further Notice of Proposed Rulemaking, ET Docket No 98-153 (released March 12, 2003)

[10] Because of hardware limitations it is necessary to scale the pulse FH system parameters and the measurement settings This is explained in more detail in Section 4

repetitiveness of frames), and bandwidth of a single pulse at the highest, lowest and intermediate hopping channels

- Measure the power level of the pulsed FH signal with peak and root-mean-square (RMS) detectors in a filter bandwidth of 50 kHz. Measurements are to be performed using a swept frequency measurement algorithm.

- Measure the peak and RMS power levels of a pulsed FH signal in a 30 kHz, 50 kHz, 100 kHz, 300 kHz, 1 MHz, 3 MHz, 5 MHz, and 20 MHz bandwidth filter centered on one of the hopping frequency channels.

- Measure the peak and RMS power levels of a dithered impulse UWB signal in a 1 MHz, 2 MHz, 3 MHz, 4 MHz, 5 MHz, 6 MHz, 8 MHz filter bandwidth and a 150 MHz filter bandwidth.

4. MEASUREMENT SETUP

The measurement setup shown in Figure C-1 will be used to generate the pulsed FH and impulse UWB signals and perform the required frequency and time domain measurements.

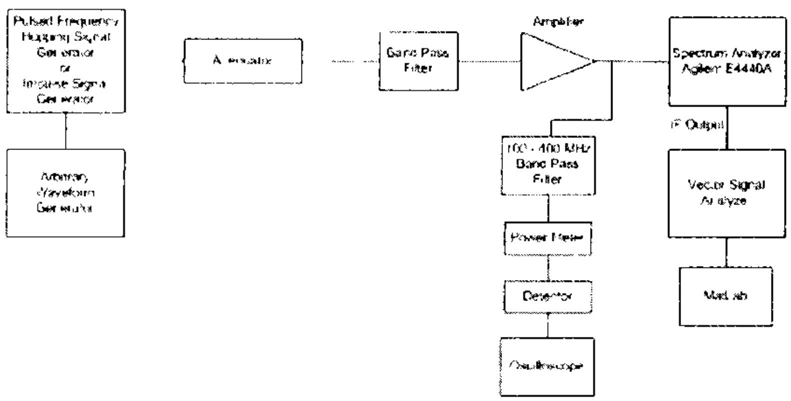

Figure C-1.

Siemens has proposed that the pulsed FH vehicular radars be permitted to operate in the 22-29 GHz frequency range as currently permitted by the Commission's Rules for impulse UWB vehicular radars. The EESS sensors operate in the 23.6-24 GHz band However, as a result of hardware limitations at these higher frequencies, these tests will use a pulsed FH signal at a center frequency of 26 MHz.[11] Hardware limitations encountered in generating the pulsed FH signal resulted in scaling the system parameters by a factor of 20. In order to perform the measurements the filter bandwidths and measurement times also had to be scaled accordingly Table C-1 provides a summary of the original and scaled pulsed FH signal parameters and the measurement equipment settings used in performing the measurements.

[11] This basically sets the carrier frequencies for the pulses and is thus of concern only in setting the frequencies to be measured

Table C-1.

Parameter	Original Value	Scaled Value
Pulse Width	50 nanosecond	1 microsecond
Pulse Repetition Frequency	1 MHz	50 kHz
Hopping Frequency Range	1 GHz	50 MHz
Number of Hop Channels	200, 100, 25	200, 100, 25
Spectrum Analyzer Resolution Bandwidth	1 MHz	50 kHz
Measurement Times	20, 10, and 2 5 milliseconds per data point	400, 200, and 50 milliseconds per data point
EESS Sensor Bandwidth	400 MHz	20 MHz
Frequency Hopping Pattern	Pseudo Random	Pseudo Random

For the pseudo random hopping pattern the first frequency from the available hop set is randomly selected. This frequency is no longer available for selection. This random frequency selection without replacement process continues until all of the frequencies in the hop set have been selected. The frequency hopping sequence then repeats beginning with the first frequency that was originally selected. This results in returning to each hopping channel on a regular periodic basis The scaling of the pulsed FH system parameters and the measurement equipment settings should have no impact on the measurement results gathered to address the questions in the FNPRM

5. MEASUREMENT PROCEDURES

5.1 COMPLIANCE MEASUREMENT PROCEDURES

The measurement procedures described below are to be used to address the questions in the Commission's FNPRM related to the techniques for pulsed FH signal compliance measurements

A The Arbitrary Waveform Generator (AWG) will be programmed to generate a pulsed FH signal with the following parameters: **Center Frequency**: 26 MHz; **PW**: 1 microsecond; **PRF** 50 kHz; **Hopping Frequency Range**: 50 MHz, **Number of Hop Channels**: 200, 100, and 25; and **Frequency Hopping Pattern**· pseudo random.

B. Using a spectrum analyzer in sweep mode, measure the emission spectrum of the pulsed FH signal operating in the hopping mode with a 100 frequency hopset. The emission spectrum should be measured to at least 20 dB below the maximum level Set up the spectrum analyzer with the following settings: **Video Bandwidth**: greater than or equal to the resolution bandwidth, **Resolution Bandwidth**: 50 kHz for the scaled-down signal, **Detection**: Peak detect, **Start Frequency**: 0 MHz (for the scaled-down signal), **Stop Frequency**: 10 MHz greater than the highest hopping frequency(60 MHz for the scaled-down signal), **Display Points**: (stop freq - start freq) / RBW (1200 points for the scaled-down signal), **Sweep Time**: (1/PRF) * (frequency bins) * 100 * Display points = (480 s for 200 bins, 240 s for 100 bins, 60 s for 25 bins - for the scaled-down signal). The sweep time is set so that peak and average power, as represented by a single data point on the monitor, is determined from enough data samples to include 100 repetitions of the entire hopping sequence. This insures that, at least, 100 pulses are sampled to determine the power parameters and is necessary because, for narrow bandwidths, only a single pulse within the entire hopping sequence will be passed through the passband for each repetition of the hopping sequence.

C. Repeat Step B using average power (RMS) detection.

D. Digitize the pulsed FH signal. The signal must be down converted so that the lowest pulse frequency is centered at a frequency equal to the reciprocal of the pulse width. The data must be acquired at a sampling frequency greater than or equal to 2.5 times the highest hop frequency (after down conversion) and must be acquired for a period of time equal to or greater than (1/PRF) * (FrBins + 6), where FrBins is the number of frequency bins in the frequency hopping scheme. The digitized time domain signal will be analyzed using a digital signal processing routine to determine the following: 1) Verify the minimum and maximum frequencies in the hop set; 2) Verify the frequency difference between the hopping channels in a hop set; 3) Verify the number of hopping channels in a hop set. 4) Verify the hopping frame pattern. Is the hopping pattern random? What is the length of the sequence? Are the frames repetitive? 5) Measure the bandwidth of a single pulse at the lowest frequency, at the highest frequency, and at 2 intermediate frequencies in the hop set These parameters are determined by breaking up the digitized data into individual pulses. A plot of five consecutive pulses will be used to verify the PRF. A plot of any single pulse will be used to verify the pulse width. Fast Fourier Transforms (ffts) of each individual plot will be used to determine the frequency hopping sequence, as well as, the length of the sequence, spacing between adjacent frequencies, and the spectrum of individual pulses.

E. Repeat Steps B through D for the 200 frequency and 25 frequency hop sets.

5.2 COMPATIBILITY STUDY MEASUREMENT PROCEDURES

The measurement procedures described below are to be used to examine whether the compliance measurements can be used in compatibility studies for assessing interference to EESS sensors

A. The AWG will be programmed to generate a pulsed FH signal with the following parameters. **Center Frequency**: 30 MHz; **PW**: 1 microsecond; **PRF**: 50 kHz; **Hopping Frequency Range**: 50 MHz; **Number of Hop Channels**: 200, 100, and 25; **Frequency Hopping Pattern**: pseudo random.

B. Using an E4440A spectrum analyzer in sweep mode, zero span, and centered on one of the hopping frequencies located midway across the span of hopping frequencies, measure the peak power of the pulsed FH signal operating in the hopping mode with a 100 frequency hopset Set up the spectrum analyzer with the following settings: **Video Bandwidth**: greater than or equal to the resolution bandwidth, **Resolution Bandwidth**: 30 kHz, **Detection**: Peak detect; **Center Frequency**: centered on one of the hopping frequencies located midway across the span of hopping frequencies; **Span**: zero span; **Display Points**: as desired, **Sweep Time**: (1/PRF) * (frequency bins) * 100 * Display points = (480 s for 200 bins, 240 s for 100 bins, 60 s for 25 bins - for the scaled-down signal). Using any single point near the center of the display, record the power.

C. Repeat Step B with resolution bandwidths of 50 kHz, 100 kHz, 300 kHz, 1 MHz, 3 MHz, 5 MHz, and 8 MHz and record.

D Repeat Steps B and C using a mean power (RMS) detector.

E. Using the Vector Signal Analyzer (VSA), digitize the 70 MHz intermediate frequency (IF) output of the E4440A spectrum analyzer set up as follows: **Center Frequency**: centered on one of the hopping frequencies located midway across the span of hopping frequencies, **Span**: zero span, **Sweep**: Single. Resolution bandwidth, video bandwidth, detection mode, display points, and sweep time can be set as desired, as these do not affect the IF output. Use the AWG to generate a pulsed FH signal with a 100 frequency hop set. After a single sweep of the spectrum analyzer is completed, the signal is digitized long enough to obtain 100 complete repetitions of the entire hopping sequence. Using digital signal processing of the baseband signal, filter to equivalent RF bandwidths of 30 kHz, 50 kHz, 100 kHz, 300 kHz, 1MHz, 3 MHz, 5 MHz, 8 MHz, and 20 MHz. Compute the sum of the squares of the filtered in-phase and quadrature signals to obtain the envelope detected signal. Then compute the peak and average power of the resulting envelope detected signal

F Repeat Steps B through E for the 200 frequency and 25 frequency hop sets.

5.3 IMPULSE UWB SIGNAL MEASUREMENTS

The measurement procedures described below are to be used to compare the power level of an impulse UWB signal at the output of a filter representing the EESS sensor filter.

A. The AWG will be programmed to control the impulse generator to develop a 50% absolute referenced dithered impulse signal with a PRF of 1 MHz. The characteristics of the impulse signal will be such that it produces a flat spectrum across a bandwidth of 150 MHz centered at 1.3 GHz.

B With an instrument setup as shown in Figure C-2, calibrate the HP8474C Detector by injecting increasing levels of a CW signal and measuring the power on the power meter and the voltage on the oscilloscope. Produce a calibration curve relating the voltage measured on the oscilloscope to the power measured on the power meter (the power meter considered as the standard).

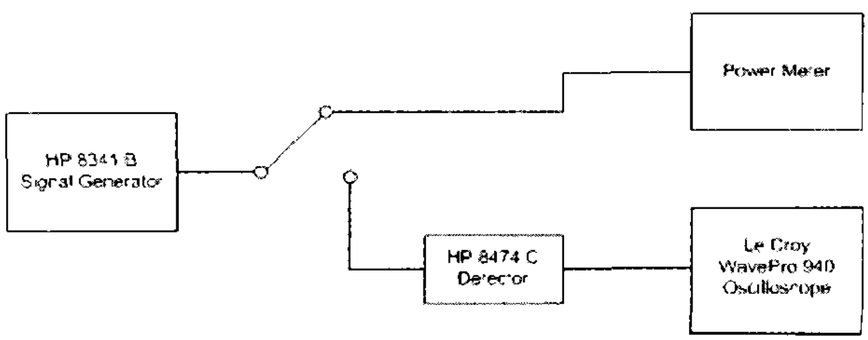

Figure C-2.

C With an instrument setup as shown in Figure C-3, calibrate the E4440A Spectrum Analyzer by injecting increasing levels of a CW signal and measuring the average power on the power meter and the spectrum analyzer (detection mode set to average power). Produce a calibration curve relating the power measured on the spectrum analyzer and the power meter (the power meter considered as the standard).

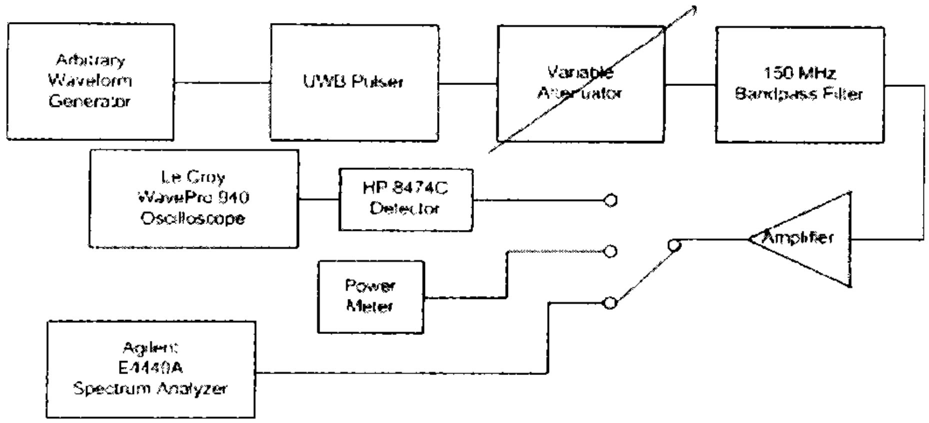

Figure C-3.

D. Set up the spectrum analyzer as follows: **Video Bandwidth**: 8 MHz or greater; **Resolution Bandwidth**: 8 MHz; **Center Frequency**: 1300 MHz; **Span**: zero; **Sweep Time**: 60 ms (100 pulses per data point); **Points Per Display**: 601. With an instrument setup as shown in Figure C-4, inject the 50%-absolute-referenced-dithered impulse signal into the detector and adjust the variable attenuator so that the signal is not compressed by the front end of the spectrum analyzer. This is accomplished by increasing the level of the signal and observing for any non-linearities in the measured peak and average power. Once the proper attenuation level is determined, use the spectrum analyzer to measure peak and average power at the following bandwidths: 1MHz, 2 MHz, 3 MHz, 4 MHz, 5 MHz, 6 MHz, and 8 MHz. Adjust the numbers using the calibration curve described in C so that the powers are referenced to the power meter. Next, switch to the power-meter path and measure the mean power passing through the 150 MHz filter; this will be the mean power measured in a 150 MHz bandwidth. Finally, switch to the oscilloscope path and measure the voltage at the detected pulse peak, and using the calibration curve produced in B, translate the power to that measured by the power meter; this will be the peak power measured in a 150 MHz bandwidth.

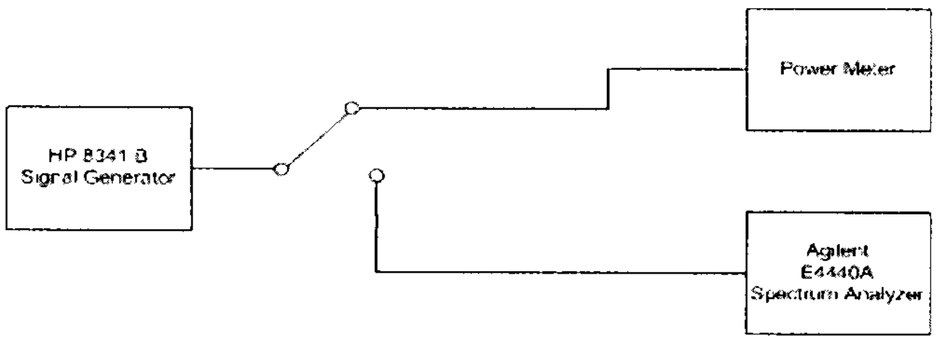

Figure C-4.

E. Using the oscilloscope measure the time waveform at the output of the detected, 150-MHz-bandwidth signal.

APPENDIX D

PROPOSED CERTIFICATION MEASUREMENT PROCEDURES FOR PULSED FREQUENCY HOPPING VEHICULAR RADAR SYSTEMS OPERATING IN THE 22-29 GHZ FREQUENCY RANGE

BACKGROUND

The Federal Communications Commission (Commission) Rules for ultrawideband (UWB) transmission systems provide for the operation of vehicular radar systems. The Short-Range Automotive Radar Association (SARA), an association composed of the world's leading automobile manufacturers and automotive component manufacturers, is working to promote the development and deployment of short-range vehicular radar systems, operating in the 22-29 GHz frequency range. These radar systems are being promoted as a core component of the next generation of collision avoidance and have the potential to reduce the incidence and severity of automobile accidents.[1] The various component manufacturer members of SARA are designing vehicular radar systems based on different modulation techniques.

In the Further Notice of Proposed Rulemaking (FNPRM) in the UWB proceeding, the Commission is proposing to permit the operation of vehicular radar systems that employ pulsed Frequency Hopping (FH) modulation under the rules for vehicular radar systems that employ impulse modulation techniques. As proposed by the Commission, the pulsed FH vehicular radar systems would operate in the same frequency range as the impulse vehicular radar systems, and would have to comply with the same peak and average Equivalent Isotropically Radiated Power (EIRP) limits. The measurement procedures developed for vehicular radar systems did not include provisions for pulsed FH signals

Appendix C describes a measurement plan used to develop of certification measurement procedures for vehicular radar systems employing pulsed FH signals. Based on the measurements performed in Appendix C, this appendix provides a proposal for the certification measurement procedures to be used for vehicular radar systems that employ pulsed FH signals.

PULSED FH SYSTEM PARAMETERS REQUIRED FOR DEVICE CERTIFICATION

The emission characteristics of a pulsed FH signal are defined by its system parameters. The applicant requesting device certification should be required to provide the following system parameters: pulse width, pulse repetition frequency (PRF), frequency hopping bandwidth, number of frequency hopping channels, hopping channel frequency separation, the time length of the frequency hopping sequence, and the frequency hopping pattern (e g., pseudo random, linear step). These parameters will define a specific mode of operation for the vehicular radar. If there are multiple operating modes the system parameters for each mode is to be provided by the applicant.

OVERVIEW OF RULES FOR UWB VEHICULAR RADAR SYSTEMS

Section 15.515 of the FCC's Rules, provide for the operation of UWB vehicular radar systems in the 22-29 GHz frequency range using directional antennas on terrestrial transportation vehicles provided the center frequency of the emission and the frequency at which

[1] These devices are able to detect the location and movement of objects near a vehicle, enabling features such as near collision avoidance, improved airbag activation, and suspension systems that better respond to road conditions

the highest radiated emission occurs are greater than 24.075 GHz. For UWB vehicular radars, the EIRP limit, measured with a root-mean-square (RMS) detector in the 23.6-24 GHz band is - 41 3 dBm/MHz The maximum allowable EIRP levels are summarized in Table 1 which shows the emission limits above 960 MHz that are applicable to unlicensed UWB vehicular radar systems. Below 960 MHz the Part 15 general emission limits are applicable.

Table 1. Unlicensed UWB Vehicular Radar Emission Limits

Frequency Band (MHz)	Maximum Allowable EIRP (dBm)
960-1610	-75.3
1610-22000	-61.3
22000-29000	-41.3
29000-31000	-51.3
Above 31000	-61.3

There is also a limit on the peak level of the emissions. The peak EIRP is 0 dBm when measured with a resolution bandwidth (RBW) of 50 MHz and 20 Log (RBW/50) dBm when measured with a resolution bandwidth ranging from 1 MHz to 50 MHz. RBW is the spectrum analyzer resolution bandwidth, in megahertz, that is actually employed in the measurement. The minimum resolution bandwidth employed is 1 MHz; the maximum resolution bandwidth that may be employed is 50 MHz [2]

The vehicular radar systems are also required to attenuate any emissions within the 23.6-24 GHz band that appear 38 degrees above the horizontal plane by 25 dB below the value of -41.3 dBm/MHz. For equipment authorized, manufactured or imported on or after January 1, 2005, this level of attenuation shall be 25 dB for any emissions within the 23.6-24 GHz band that appear 30 degrees or greater above the horizontal plane For equipment authorized, manufactured or imported on or after January 1, 2010, this level of attenuation shall be 30 dB for any emissions within the 23.6-24 GHz band that appear 30 degrees or greater above the horizontal plane. For equipment authorized, manufactured or imported on or after January 1, 2014, this level of attenuation shall be 35 dB for any emissions within the 23.6-24 GHz band that appear 30 degrees or greater above the horizontal plane These levels of attenuation can be achieved through the antenna directivity, through a reduction in output power, or any other means.[3]

OVERVIEW OF CERTIFICATION MEASUREMENT PROCEDURES

The general measurement setup used in the certification measurements is shown in Figure 1.

[2] 47 C F R § 15 515(d), (f)

[3] 47 C F R § 15 515(c)

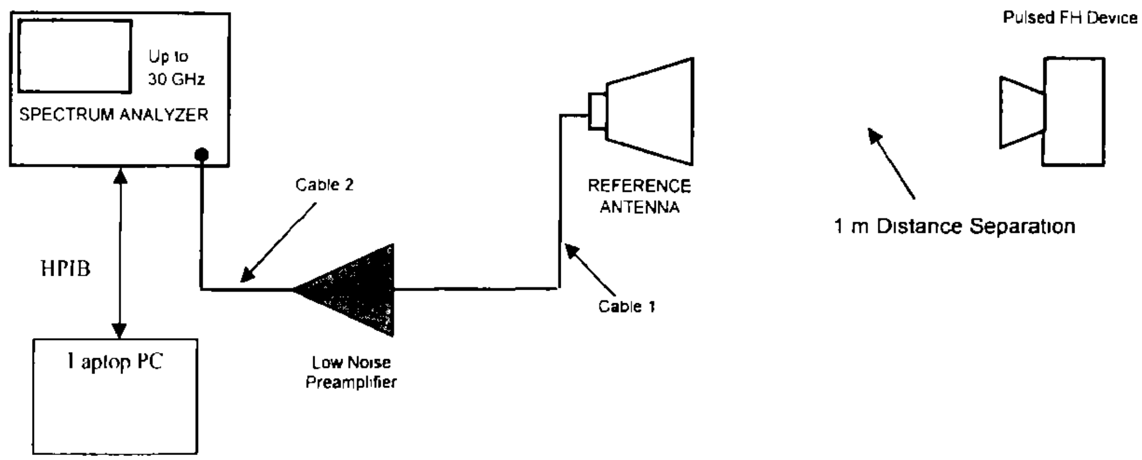

Figure 1. General Measurement Setup

The certification measurements will require two test setups. The first test setup will be used to measure the emission characteristics of the unit under test (UUT) primarily within the 22 to 29 GHz frequency range and the antenna gain characteristics. The second test setup will be used to measure emission characteristics in the 1 to 3 GHz frequency range. Both test setups will use the equipment shown in Figure 1, the only difference will be the applicable frequency range of the preamplifier and the measurement antenna.

The 22 to 29 GHz frequency range test setup will use a 1 meter separation distance with no surface that could provide significant reflections in the vicinity of the test setup. The UUT including the transmit antenna is to be located at a height of approximately 1 to 2 meters. The UUT antenna support must be such that the antenna can rotated (in the horizontal plane) from +90 degrees to -90 degrees, relative to direct alignment with the measurement antenna. The rotation should be such that the antenna can be moved in 5 degree increments. The required commercially available measurement equipment includes.

- Spectrum analyzer with a peak detector, RMS detector, and maximum hold[4] capabilities, and capable of operating up to 30 GHz,

- Measurement antenna with a gain on the order of 15 dBi over the approximate frequency range of 18 to 26 GHz,

- Low noise preamplifier with a gain of at least NF + L + 5 dB,where NF is the noise figure of the spectrum analyzer, and L is the loss of the cable connecting the low noise preamplifier to the spectrum analyzer. The low noise preamplifier should have a noise figure of less than 2 dB over the frequency range of 18 to 26 GHz;

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[4] The maximum hold capability retains the maximum value for each point on the spectrum analyzer display over the selected number of display scans

- Low loss cable to connect measurement antenna to low noise preamplifier input with a cable loss on the order of 0.2 dB at 24 GHz;

- Suitable cable(s) are required to connect the low noise preamplifier output to the spectrum analyzer. This connection might require a variable attenuator to avoid saturation;

- A personal computer connected to the spectrum analyzer is recommended to control the analyzer and to store the measured data

The 1 to 3 GHz measurement setup requires the following commercially available measurement equipment.

- Spectrum analyzer with a peak detector, RMS detector, and maximum hold capabilities and capable of operating up to 30 GHz;

- Measurement antenna with a gain on the order of 10 dBi over the approximate frequency range of 1 to 3 GHz (a minimum antenna gain of 8 dBi is required across the 1170 to 1580 MHz frequency range),

- Low noise preamplifier with a gain of at least NF + L + 5 dB, where NF is the noise figure of the spectrum analyzer, and L is the loss of the cable connecting the low noise preamplifier to the spectrum analyzer. The low noise preamplifier should have a noise figure of less than 2 dB over the frequency range of 1 to 3 GHz;

- Low loss cable to connect measurement antenna to low noise preamplifier input with a cable loss on the order of 0.2 dB at 2 GHz;

- Suitable cable(s) are required to connect the low noise preamplifier output to the spectrum analyzer. This connection might require a variable attenuator to avoid saturation;

- A personal computer connected to the spectrum analyzer is recommended to control the analyzer and to store the measured data

The test setup including and test equipment must be calibrated so that the EIRP of the UUT can be measured. This calibration must be applicable across the frequency range that is defined by the operating frequency range of the measurement equipment combination. If the measurements are not performed in an anechoic chamber, the signal environment must be monitored to determine if there are any extraneous signals.

Measurement of Peak Power Levels, -10 dB Bandwidth, and Center Frequency

These measurements are to be carried out using the first measurement setup The UUT antenna is to be pointed directly at the measurement antenna and the UUT is to be mounted in an upright position as it would be mounted on a vehicle. With the UUT operating in the frequency hopping mode[5] and the spectrum analyzer set to the peak detector mode with a resolution bandwidth of 3 MHz and video bandwidth of at least 3 MHz. The peak EIRP emissions of the UUT should be measured across the range of 22 to 26 GHz. The dwell time for each 3 MHz interval is 2 seconds and the peak value for each interval is to be recorded.

The data is then to be analyzed to determine the maximum of the peak power values and the lowest frequency where a peak value is 20 dB and 10 dB below the maximum peak value. The highest frequency at which the peak value is 10 dB below the maximum peak value will also be determined. If the highest frequency 10 dB down point is not contained within the measured data, the frequency range of the peak measurements must be extended to the 26 to 29 GHz range.

For certification the maximum peak value is not to exceed -24 dBm in the 3 MHz resolution bandwidth, the difference in frequency between the two 10 dB down points, which defines the UWB bandwidth, is to be at least 500 MHz. The mid-point in frequency between the 10 dB down points is to be 24.075 GHz or greater. The 20 dB down point on the lower frequency end must be greater than or equal to 22 GHz and the 10 dB down point at the upper frequency end of the UUT spectrum must be less than or equal to 29 GHz.

Measurement of Average Power Levels

These measurements are to be carried out using the first test setup. The UUT antenna is to be pointed directly at the measurement antenna with the UUT antenna in the upright position. With the UUT operating in the frequency hopping mode and the spectrum analyzer set to the RMS detector with a resolution bandwidth of 1 MHz and video bandwidth of at least 3 MHz, the average EIRP emission levels are to be measured across the range of the UUT 10 dB bandwidth. The average emissions are to be measured over a 1 millisecond time interval for each 1 MHz interval. This average EIRP measurement is to be repeated, with the analyzer in the maximum hold mode, until there is no significant increase in any of the maximum hold values. No significant increase would be less than 3 dB. The maximum RMS emission level for each 1 MHz interval is to be recorded. The spectrum analyzer sweep time, sweep width, and number of frequency bins (number of points on the display) need to be properly coordinated to yield the required data. For example, if there are 1000 frequency bins, set the sweep width to 1 GHz and set the sweep time to 1 second. This will result in a 1 millisecond per bin integration time and a 1 MHz frequency interval per bin The maximum values of multiple sweeps is to be determined for each frequency bin as the frequency hopping period[6] may last longer than the 1 millisecond integration time. The 10 dB bandwidth of the UUT may have to be segmented to obtain the full data set. For the above example, only 1 GHz is covered for the set of selected parameters. For certification the maximum of all of the average EIRP measurements each in a 1 MHz resolution bandwidth over a 1 millisecond time interval is not to exceed –41.3 dBm. If the maximum value of the average EIRP measurement is less than -41.3 dBm, the reduced EIRP level can be used in assessing the vertical antenna gain limits

Measurements of Vertical Antenna Gain

These measurements are to be carried out using the first test setup. However, for these

[5] If the UUT has more than one mode of operation, a complete set of all measurements are required for each mode

[6] The frequency hopping period is the time it takes to revisit the same frequency in the hop set.

tests the UUT is to be mounted on its side (rotated 90 degrees from the upright position). The UUT is to be operated in the frequency hopping mode. The spectrum analyzer is to be in the peak detector mode with a resolution bandwidth of 3 MHz and a video bandwidth of at least 3 MHz. For these tests the spectrum analyzer will be operated in the zero span mode at frequencies of 24 GHz, 23.875 GHz, 23.750 GHz, and 23.6 GHz. If the lower frequency point defining the 10 dB bandwidth is greater than 23.6 GHz this frequency should be used for the antenna measurements instead of 23.6 GHz

The peak power measurements are to be made over a 2 second interval for each of the four test frequencies with the antenna of the UUT and the measurement antenna directly aligned (this is referred to as boresight). The UUT is then to be realigned 5 degrees from boresight and the peak measurements at each of the four frequencies are to be repeated. This procedure is repeated in 5 degree increments until the UUT is 90 degrees from boresight. The UUT is then to be returned to boresight and a data set measured. The UUT antenna is then to be rotated in 5 degree increments in the opposite direction until the UUT antenna is 90 degrees from boresight. The values of antenna gain reduction are then determined from the difference between the boresight power level and the power level measured at each off-axis (5 degree increments) angle.

The EIRP levels in the 23.6-24 GHz band have to be reduced by 25 dB relative to the -41 3 dBm/MHz limit for elevation angles 38 degrees or more from boresight. This applies to all equipment manufactured or imported prior to January 1, 2005. For equipment manufactured or imported after January 1, 2005 the reduction of the EIRP in the 23.6-24 GHz band must be 25 dB for angles 30 degrees or more from boresight. The attenuation of the EIRP in the 23.6-24 GHz band is to be increased to 30 dB by January 1, 2010, further increased to 35 dB by January 1, 2014.

For certification, the sum of the reduction if any in the EIRP (from the -41.3 dBm limit) expressed in dB and the antenna gain reduction in dB must be at least the above values. That is 25 dB for angles 38 degrees above the horizontal and then 25, 30, and 35 dB for angles 30 degrees above the horizontal as required in the time-phased schedule for the emission limits in the 23.6-24 GHz band.

Measurement of Out-Of-Band Average Power Levels

These measurements are to be carried out using the first test setup. Again the UUT antenna is to be aligned with the measurement antenna. With the UUT operating in the frequency hopping mode and the spectrum analyzer set to the RMS detector with a resolution bandwidth of 1 MHz and a video bandwidth of at least 3 MHz, average EIRP emission levels are to be measured.

For these measurements, the spectrum analyzer should be operated in the zero span mode. The average power is to be measured over a 10 millisecond interval with the UUT on and a 10 millisecond interval with the UUT turned off, at 1 GHz intervals from the low end of the test setup applicable frequency range to the frequency of the lower –10 dB bandwidth point. The average power is to also be measured with the UUT on and then turned off at both the –20 dB and –10 dB lower frequency points. These -20 dB and -10 dB frequencies were determined earlier. The average power is to be measured from the highest -10 dB bandwidth point to the highest test setup applicable frequency in 1 GHz steps. The average power is to be measured over a 10 millisecond interval with the UUT turned on and then turned off.

For certification, the maximum allowable EIRP levels are as stated in Table 1 which shows the emission limits above 960 MHz, expressed in terms of the maximum allowable EIRP levels, that are applicable to unlicensed UWB vehicular radar systems. Below 960 MHz the Part 15 general emission limits are applicable.

Measurement of Average Power in the 1164-1700 MHz Frequency Range

These measurements are to be carried out using the second test setup. The UUT antenna is to be pointed directly at the measurement antenna. The UUT is to be operated in the frequency hopping mode. The spectrum analyzer is to be operated in the zero span mode using the RMS detector function with a resolution bandwidth of 1 MHz and a video bandwidth of at least 3 MHz. At each fixed frequency the average power is to be measured over a 10 millisecond interval with the UUT turned on and then with the UUT turned off.

Average power measurements are to be made at the following frequencies: 1171.5 MHz, 1176.5 MHz, 1181.5 MHz, 1227.6 MHz, 1575.4 MHz, 1615 MHz, 1700 MHz. Measurements are then to be made in 100 MHz steps to the highest frequency of the test setup applicable frequency range.

For certification, the EIRP measured at each frequency with the UUT turned on cannot exceed the levels in Table 1.

CALIBRATION AND ENVIRONMENTAL SIGNAL MONITORING

The test setup (required to include path loss) and test equipment must be calibrated so that the EIRP of the UUT can be measured. This calibration must be applicable across the frequency range that is defined by the operating frequency range of the measurement equipment combination. As part of the test setup and calibration with the UUT turned on, measurements should be performed to determine if the low noise preamplifier is being saturated. If saturation occurs, attenuation can be properly employed to eliminate the problem.

The applicable frequency range, for each measurement setup will be determined from the operating frequency range of the measurement antenna and the low-noise preamplifier in combination. Thus, if the antenna is rated from 18 to 28 GHz and the low-noise preamplifier from 20 to 30 GHz, the applicable frequency range of the measurement setup is 20 to 28 GHz. The applicable frequency range is used to establish certain measurement limits.

If the measurements are not performed in an anechoic chamber, the signal environment must be monitored to determine if there are any extraneous signals. In cases where such signals are present, in the frequency ranges of concern, steps should taken to turn off the signals or to shield them from the test setup. If the presence of such signals is significant the test site should not be used. If the presence of such signals is relatively minimal the data for those effected frequencies should be ignored.

APPENDIX E

COMPARATIVE ANALYSIS ASSESSING THE POTENTIAL IMPACT TO EESS SENSOR RECEIVERS FROM IMPULSE AND PULSED FREQUENCY HOPPING SIGNALS USED BY VEHICULAR RADAR SYSTEMS

INTRODUCTION

The NTIA performed an analysis to assess the potential impact of vehicular radars employing impulse signals to the passive sensors operated in the Earth Exploration-Satellite Service (EESS) by the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) in the 23.6-24 GHz frequency band.[1] In order to assess the potential interference impact of allowing vehicular radars using pulsed frequency-hopping (FH) signals to operate under the requirements of the rules adopted in the ultrawideband (UWB) First Report and Order (R&O), a comparative analysis was carried out. That is the interference level in the EESS sensor receiver from several impulse and pulsed FH radar signals was computed. These results were comparative in that certain parameters that are common (e g., propagation loss) to all the interference cases considered were not included in the computations. The exclusion of these common parameters does not change the comparative results The comparative analysis examined impulse signals and pulsed FH signals with different characteristics. The analysis will also examine what impact the specific pulsed FH characteristics such as pulse width, pulse repetition frequency, hop-channel spacing will have on compatibility with EESS sensor receivers.

UWB RULES FOR VEHICULAR RADARS

Section 15.515 of the FCC's Rules, provide for the operation of UWB vehicular radar systems in the 22-29 GHz frequency range using directional antennas on terrestrial transportation vehicles provided the center frequency of the emission and the frequency at which the highest radiated emission occurs are greater than 24.075 GHz. It is envisioned that these devices will be able to detect the location and movement of objects near a vehicle, enabling features such as near collision avoidance, improved airbag activation, and suspension systems that better respond to road conditions. The emissions must be attenuated by greater than 25 dB for elevations 35 degrees or more above the horizontal plane. The attenuation is to be increased to 30 dB by 2010 and further increased to 35 dB by 2014. These levels of attenuation can be achieved through the antenna directivity, through a reduction in output power or any other means.

For UWB vehicular radars, the EIRP limit, measured with a root-mean-square (RMS) detector in the 23.6-24 GHz band is -41.3 dBm/MHz. There is also a limit on the peak level of the emissions. The peak EIRP is 0 dBm when measured with a resolution bandwidth (RBW) of 50 MHz and 20 Log (RBW/50) dBm when measured with a resolution bandwidth ranging from 1 MHz to 50 MHz. RBW is the spectrum analyzer resolution bandwidth, in megahertz, that is actually employed in the measurement. The minimum resolution bandwidth to be employed is 1 MHz; the maximum resolution bandwidth that may be employed is 50 MHz. In all cases, the certification measurement approach and associated emission limits contained in the UWB R&O were considered in establishing the permitted radar emission limits.

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[1] Letter from William T Hatch, Associate Administrator, Office of Spectrum Management, National Telecommunications and Information Administrator, to Mr Edmond J Thomas, Chief, Office of Engineering and Technology, Federal Communications Commission (February 13, 2002) at Attachment 2

PEAK AND AVERAGE POWER LIMITED SIGNALS

In the comparative analysis a determination is made as to whether a signal considered in the analysis is peak or average power limited. As described above, the Commission's Rules, establish limits on the peak and average power levels as follows:

Peak power of the waveform referenced to 50 MHz (P_{50}) $\leq$ 0 dBm

Average power measured in a 1 MHz bandwidth (A_m) < -41.3 dBm

To determine whether a signal is peak or average power limited the following conditions will apply:

$$A_m = P_{50} - C$$

If C > 41.3 the signal is peak power limited

If C < 41.3 the signal is average power limited

For an example of a peak limited signal, if A_m is -41.3 dBm then P_{50} would be 1.7 dBm, if C is 43 This would violate the 0 dBm peak limit, thus the peak power must be reduced. Therefore, this signal would be peak power limited. That is P_{50} = 0 dBm and A_m = -43 dBm/MHz. For an average power limited signal, if A_m is -41.3 dBm and C = 40, then P_{50} would be -1.3 dBm. This signal would be average power limited becasue the peak power can be increased by 1.3 dB before the 0 dBm limit is exceeded, but it is limited by the average power limit of -41 3 dBm. The main point is that for the UWB signals there is a fixed 41.3 dB difference between the peak power in a 50 MHz bandwidth and the average power in a 1 MHz bandwidth that must be maintained.

COMPARATIVE ANALYSIS OF INTERFERENCE TO EESS SENSOR RECEIVERS

The comparative analysis considered impulse non-dithered, impulse dithered, and pulsed FH signals For non-dithered signals there are spectral lines at the pulse repetition frequency (PRF).[2] Dithering of the pulses in the time domain spreads the spectral line content of a signal in the frequency domain making the signal appear more noise-like. The characteristics of the pulsed FH signals are specified in terms of hopping frequency range, pulse width (PW), hopping sequence, number of hop channels, and PRF.

For the pulsed FH signals, the overlapping of hop channels is from the perspective of measuring the average power with a 1 MHz RBW. If the hopping channels are closely spaced, with respect to the bandwidth of an individual radar pulse, then significant power from adjacent hop channels can fall into the spectrum analyzer (SA) RBW thus apparently increasing the average power of the hop channel being measured. If the hop channels are more widely spaced this overlap effect is not significant. However, if the overlap causes an increase in the measured average power this must be taken into account. The effect of overlapping pulses will not cause a similar increase in the peak power.

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[2] The PRF defines the number of pulses transmitted per unit time (one second) The PRF also effects the spectral line magnitude, spacing, and the percentage of time that the pulses are present.

10 MHz PRF Non-Dithered Impulse Signal

The first signal investigated was for an impulse radar with pulses having a one nanosecond PW and a constant (non-dithered) PRF of 10 MHz. A 10 MHz PRF represents an inter-pulse period of 0.1 microsecond, which is the round-trip-time for a radar to target separation of 15 meters.[3] This waveform has a duty cycle (DC) of:

$$DC = -10 \log (PRF \times PW) = 20 \text{ dB},$$

and thus the relationship between the peak power (P_w) and the average power (A_w) for this waveform is:

$$A_w = P_w - DC = P_w - 20 \text{ dB}$$

According to the UWB R&O, this signal is to be measured using a SA with a RBW of 1 MHz With a constant PRF of 10 MHz, this signal consists of spectral lines each spaced 10 MHz apart. When measured with a 1 MHz RBW, the SA can see at most only one spectrum line and this occurs only when the SA is tuned to a line. For the case of one line in the resolution bandwidth, the measured peak (P_m) and average (A_m) power levels will be the same (e.g., $P_m = A_m$).

To determine the peak and average power from the 1 MHz bandwidth measured values, P_m is corrected by 20 log (waveform bandwidth) /(measurement bandwidth) and A_m is corrected by 10 log of the same bandwidth ratio. For the waveform discussed here, the waveform bandwidth is 1/PW or 1 GHz. However, these corrections do not completely hold for the present case because the power measured is not really the power in a 1 MHz bandwidth. It is the power in a 10 MHz bandwidth (the spacing between the lines). If one were to step this 1 MHz measurement bandwidth in 1 MHz steps across this impulse signal, one would find that in nine out of ten steps the signal would not be measured. Furthermore, if one were to measure this signal in a 10 MHz bandwidth (recognizing that most SAs do not have a 10 MHz resolution bandwidth capability), you would obtain the same values of P_m and A_m as that measured with a 1 MHz bandwidth centered on the spectral line. Thus to obtain the value of P_w from the measured value of P_m (measured in a 1 MHz bandwidth), the correction is 20 log (1 GHz/10 MHz) so that:

$$P_w = P_m + 40 \text{ dB}$$

To obtain the value of A_w from the measured value of A_m (measured in a 1 MHz bandwidth), the correction is 10 log (1 GHz/10 MHz) so that:

$$A_w = A_m + 20 \text{ dB}$$

For the signal being considered $P_m = A_m$ and so the corrected measurements for P_w and A_w show a peak-to-average ratio of 20 dB which agrees with the basic waveform.

The Commission's Rules limit the peak power, as adjusted for a reference bandwidth of 50 MHz (P_{50}), to 0 dBm. The average power, in a 1 MHz bandwidth, is limited to – 41 3 dBm. That is the ratio of peak power (in 50 MHz) to the average power (in 1 MHz) is limited to 41.3 dB. Thus some systems (usually lower PRF systems) can be peak power limited and other signals (usually higher PRF systems) can be average power limited.

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[3] The range is computed from ½x(Round Trip Time)x(Speed of Light)

The measured peak power (in 1 MHz) is corrected by 20 log 50 to determine $P_{50} = P_m + 34$ dB. For this signal $P_{50} = A_m + 34$ dB (for this waveform $P_m = A_m$) and the limiting condition is the average power of - 41.3 dBm. If this average power is corrected to determine the average power of the basic waveform, one obtains:

$$A_w = -41.3 \text{ dBm} + 10 \log (1 \text{ GHz}/10 \text{ MHz}) = -21.3 \text{ dBm}$$

In this analysis, the EESS sensor receiver is modeled as a band pass filter (very wide bandwidth) followed by an integrator. The integration time is long compared to the filter response time and to the inter-pulse period of the vehicular radar waveform. The EESS sensor minimum integration time is on the order of 2 millisecond. Thus, the average power of the interference at the output of the band pass filter will determine the impact on the EESS sensor receiver.

For the signal under consideration (- 21 3 dBm average power in 1 GHz), the average power output of the EESS sensor receiver filter with a 400 MHz bandwidth is:

$$-21.3 \text{ dBm} + 10 \log (400 \text{ MHz}/1\text{GHz}) = -25.3 \text{ dBm}$$

This value must be further adjusted for propagation loss, antenna gains, etc. to estimate the actual interference power from the one radar. However, these extra loss values should be the same across all the signal cases being analyzed and thus have no effect on a comparative analysis Since the actual total interference impact of automotive radars to the EESS sensor receiver is due to an aggregate effect and because the parameter of concern is average power, one can add the average power attributed to each radar to determine the actual ensemble interference It should be remembered that these radars should not be operated so as to be coherent.

1 MHz PRF Non-Dithered Impulse Signal

Similarly, an impulse radar with a one nanosecond PW and a constant PRF of 1 MHz has a duty cycle:

$$DC = -10 \log (PRF \times PW) = 30 \text{ dB}$$

The relationship between P_w and A_w for this waveform is:

$$A_w = P_w - 30 \text{ dB}$$

For this waveform, a 1 MHz resolution bandwidth would contain one spectral line and again $P_m = A_m$. However, there will be one line in every 1 MHz step across the radar emission spectrum so that the measured spectral density is the power in 1 MHz. The peak power of the waveform as determined by correcting P_m is

$$P_w = P_m + 20 \log (1 \text{ GHz}/1 \text{ MHz}) = P_m + 60 \text{ dB}$$

and the determination of the average power of the waveform is:

$$A_w = A_m + 10 \log (1 \text{ GHz} / 1 \text{ MHz}) = A_m + 30 \text{ dB}$$

Since $A_m = P_m$, the peak-to-average ratio of the waveform is 30 dB as stated previously.

The peak power referenced to 50 MHz as determined according to the Commission's Rules is

$$P_{50} = P_m + 20 \log (50 \text{ MHz}/1 \text{ MHz}) = P_m + 34 \text{ dB}$$

which is limited to 0 dBm and A_m is limited to - 41.3 dBm/MHz. Similar to the 10 MHz non-dithered signal, this signal is average power limited. Thus, the limiting constraint is A_m = - 41.3 dBm and A_w will be limited to:

$$A_w = - 41\ 3 \text{ dBm} + 10 \log (1 \text{ GHz}/1 \text{ MHz}) = -11.3 \text{ dBm}$$

Considering this at the output of a 400 MHz EESS receiver filter will result in an average power of

$$-11.3 \text{ dBm} + 10 \log (400 \text{ MHz}/1 \text{ GHz}) = -15.3 \text{ dBm}$$

This is 10 dB higher than the 10 MHz PRF non-dithered impulse signal.

Dithered Impulse Signal

If the impulse radar is dithered so that the radar signal looks noise-like, the comparative EESS sensor receiver interference power can also be estimated. However, with the wide EESS sensor receiver bandwidth (nearly comparable to the impulse spectrum bandwidth), it could be difficult to make the signal truly noise-like. The signal could look noise-like to a SA with a 1 MHz resolution bandwidth and here the SA would show an approximate 10 dB peak-to-average ratio. Thus, using the Commission's procedure, the peak power level referenced to 50 MHz relative to the average power in one MHz would be:

$$P_{50} = A_m + 10 \text{ dB} + 20 \log 50 = A_m + 44\text{dB}$$

above the average power level (measured in 1 MHz) and the signal would be peak limited Because, as previously explained the UWB Rules effectively limit this ratio to 41.3 dB. The average power would have to be reduced by 2.7 dB to a level of - 44 dBm (in one MHz) and then the computed peak (relative to 50 MHz) would be 0 dBm. This average power would result in an average power in the EESS sensor receiver of·

$$-44 \text{ dBm} + 10 \log (400 \text{ MHz}/1 \text{ MHz}) = -18 \text{ dBm}$$

which is between the values computed for the 1 MHz and 10 MHz non-dithered impulse signals.

Pulsed FH Signal (Partial Overlap of Hop Channels)

For this analysis, the following pulsed FH system characteristics are considered:

Hopping frequency range - 1 GHz with hopping through out the 23.6 to 24 GHz band;

Number of hop channels - 100, resulting in a 10 MHz spacing between hop channels;

PW - 50 nanoseconds, resulting in a pulse bandwidth of 20 MHz, Hopping sequence - sampling without replacement to define the order for one cycle This cycle is then repeated resulting in the return to each hopping channel on a regular periodic basis;

PRF - 1 MHz.

Because of the partial overlapping of hop channels, measuring the average power in a 1 MHz measurement bandwidth the average power would be twice the average power of a single channel without overlap. An additional one-half the average power of the single channel being contributed by the next adjacent lower hopping channel and a similar one-half from the next higher adjacent channel Beyond the two adjacent hop channels there should be no significant contribution to an increase in average power due to overlap because of spectral fall-off of a pulse.[4]

With a PRF of 1 MHz and 100 hopping channels, one would expect to see spectral lines with a 10 kHz spacing, when viewed by a SA. This is due to the hopping sequence repeating every 100 microseconds ($1/1\times10^6 \times 100$). This is similar to the repeating of the Global Positioning System coarse/acquisition code sequence (every 1 millisecond) that results in a line spectra with a 1 kHz spacing Thus, when measured with a 1 MHz resolution bandwidth, there should be no concern for considering the occurrence of a single spectral line, since there will be 100 lines within a 1 MHz bandwidth.

The duty cycle of the hopping waveform is:

$$DC = -10 \log (PRF \times PW) = 13 \text{ dB}$$

For an individual hopping channel, the duty cycle, because of the hopping sequence assumed, would be:

$$DC_h = -10 \log (PW \times PRF/\text{No. of channels}) = 33 \text{ dB}$$

If the peak power of a pulse is set to P_w, then the average power on a single hop channel would be:

$$A_{wh} = P_w - 33 \text{ dB}$$

with both P_w and A_{wh} referenced to a 20 MHz bandwidth (e.g., pulse bandwidth). This computation of A_{wh} ignores power from adjacent hop set pulses. When measured in a 1 MHz bandwidth, the peak power (P_m) would be:

$$P_m = P_w - 20 \log (20 \text{ MHz}/1 \text{ MHz}) = P_w - 26 \text{ dB}$$

The pulses that overlap in the frequency domain are resolved in the time domain, when measured in a 1 MHz bandwidth. That is, the peak power will not increase because of the frequency overlap.

The average power (including signal overlap in the frequency domain) would be:

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[4] The pulse is represented by a sinx/x funtion with the first sidelobe down 13 dB, the second sidelobe down 17 8 dB, and the third sidelobe down 20 3 dB

$$A_m = P_w - 33\ \text{dB} - 10\log(20\ \text{MHz}/1\ \text{MHz}) + 3\ \text{dB} = P_w - 43\ \text{dB}$$

The 3 dB factor takes into account the overlapping pulses in the measurement bandwidth. Adjusting P_m for a 50 MHz bandwidth results in:

$$P_{50} = P_w - 26\text{dB} + 20\log(50\ \text{MHz}/1\ \text{MHz}) = P_w + 8\ \text{dB}$$

Comparing the P_{50} to the measured average power of P_w - 43 dB indicates that the frequency hopping signal will be peak power limited (according to the emission limits) not average power limited. Furthermore, the waveform pulse peak power is limited to -8 dBm to satisfy the constraint that the peak power referenced to 50 MHz (P_w + 8 dB) is limited to 0 dBm.

Thus, the peak power measured in a 1 MHz bandwidth would be:

$$P_m = -8\ \text{dBm} - 26\ \text{dB} = -34\ \text{dBm}$$

and the corresponding average power would be:

$$A_m = -8\ \text{dBm} - 43\ \text{dB} = -51\ \text{dBm}$$

Because of the minimum integration time of the EESS sensor receiver, this average value must be measured over a period of less than or equal to 2 millisecond. That is a steady state average value must be attained in this time period. The alternative is to measure samples of average power level over a number of time periods less than or equal to 2 millisecond across the 23 6 - 24 GHz band and compare the maximum value to the limit for compliance.

With the EESS sensor receiver bandwidth of 400 MHz, the peak power out of the filter will be -8 dBm as the receiver would see the complete (resolved) 20 MHz wide pulse. In the 400 MHz bandwidth, the EESS sensor receiver would see 40 hop channels (10 MHz hop channel spacing) plus one-half the power of a pulse on each end of the 400 MHz bandwidth because of spectral overlap. This is equivalent to 41 hop channels for a repetitive hopping sequence based on sampling without replacement to define the sequence for a single cycle. The determination of the average power in the 400 MHz bandwidth requires first computing the effective duty cycle. The duty cycle of the complete waveform was previously shown to be - 10 log (PRF x PW) = 13 dB. However, in the 400 MHz only an effective 41 out of 100 hopping channels will be seen. Thus, the PRF used in the waveform duty cycle determination must be reduced by the ratio of 41/100. This effective duty cycle is then:

$$DC_e = -10\log(\text{PRF} \times 0.41 \times \text{PW}) = 16.9\ \text{dB}$$

and the average power is 16.9 dB below the peak power or - 8 dBm - 16.9 dB = -24.9 dBm

Instead of defining the peak power in a 50 MHz bandwidth, the peak power can be defined in the spectral bandwidth of the pulse. For this example the bandwidth would be 20 MHz. Limiting the peak power to 0 dBm in a 20 MHz bandwidth would increase the peak power in the EESS sensor bandwidth to 0 dBm and the average power in the sensor bandwidth would be -16.9 dBm

Pulsed FH Signal (Complete Overlap of Hop Channels)

For this analysis, the following pulsed FH system characteristics are considered:

Hopping frequency range - 1 GHz with hopping through out the 23.6 to 24 GHz band;

Number of hop channels - 200, resulting in a 5 MHz spacing between hop channels;

PW - 50 nanoseconds, resulting in a pulse bandwidth of 20 MHz;

Hopping sequence - sampling without replacement to define the order for one cycle. This cycle is then repeated resulting in the return to each hopping channel on a regular periodic basis,

PRF - 1 MHz

Looking at the average power in a 1 MHz measurement bandwidth the level would approach 6 dB or four times the average power of a single channel without overlap. An additional average power of a single hop channel being contributed by the next adjacent lower hopping channel and similarly by the next adjacent higher hopping channel. The second adjacent channels would each contribute one-half the average power of a single channel. Beyond the first and second adjacent hop channels there should be no significant contribution to an increase in average power due to overlap because of spectral fall-off of a pulse.

The duty cycle of the hopping waveform is:

$$DC = -10 \log (PRF \times PW) = 13 \text{ dB}$$

For an individual hopping channel, the duty cycle, because of the hopping sequence assumed, would be:

$$DC_h = -10 \log (PW \times PRF/\text{No of channels}) = 36 \text{ dB}$$

If the peak power of a pulse is set to P_w, then the average power on a single hop channel would be:

$$A_{wh} = P_w - 36 \text{ dB}$$

with both P_w and A_{wh} referenced to a 20 MHz bandwidth. This computation of A_{wh} ignores power from adjacent hop set pulses. When measured in a 1 MHz bandwidth, the peak power (P_m) would be

$$P_m = P_w - 20 \log (20 \text{ MHz}/1 \text{ MHz}) = P_w - 26 \text{ dB}$$

The pulses that overlap in the frequency domain are resolved in the time domain, when measured in a 1 MHz bandwidth. That is, the peak power will not increase because of the frequency overlap.

The average power (including signal overlap in the frequency domain) would be

$$A_m = P_w - 36 \text{ dB} - 10 \log (20 \text{ MHz}/1 \text{ MHz}) + 6 \text{ dB} = P_w - 43 \text{ dB}$$

The 6 dB factor in the above equation accounts for the overlapping pulses in the measurement bandwidth. Adjusting P_m for a 50 MHz bandwidth, results in:

$$P_{50} = P_w - 26\text{dB} + 20 \log (50 \text{ MHz}/1 \text{ MHz}) = P_w + 8 \text{ dB}$$

Comparing the P_{50} to the measured average power of P_w - 43 dB indicates that the frequency hopping radar will be peak power limited (according to the emission limits) not average power limited. Furthermore, the waveform pulse peak power is limited to -8 dBm to satisfy the constraint that the peak power referenced to 50 MHz (P_w + 8 dB) is limited to 0 dBm.

Thus, the peak power measured in a one MHz bandwidth would be:

$$P_m = - 8 \text{ dBm} - 26 \text{ dB} = -34 \text{ dBm}$$

and the corresponding average power would be:

$$A_m = -8 \text{ dBm} - 43 \text{ dB} = -51 \text{ dBm}$$

With the EESS sensor bandwidth of 400 MHz, the peak power out of the filter will be -8 dBm as the receiver would see the complete (resolved) 20 MHz wide pulse. In the 400 MHz bandwidth, the EESS sensor receiver would see 80 hop channels (400/1000 x 200) plus 1.5 times the power of a pulse on each end of the 400 MHz bandwidth because of spectral overlap This is equivalent to 83 hop channels for a repetitive hopping sequence based on sampling without replacement to define the sequence for a single cycle. The determination of the average power in the 400 MHz bandwidth requires first computing the effective duty cycle. The duty cycle of the complete waveform was previously shown to be - 10 log (PRF x PW) = 13 dB. However, in the 400 MHz bandwidth only an effective 83 out of 200 hopping channels will be seen. Thus, the PRF used in the waveform duty cycle determination must be reduced by the ratio of 83/200. This effective duty cycle is then:

$$DC_e = - 10 \log (PRF \times 0.42 \times PW) = 16.8 \text{ dB}$$

and the average power is 16.8 dB below the peak power or - 8 dBm -16.8 dB = -24.8 dBm

Instead of defining the peak power in a 50 MHz bandwidth, the peak power can be defined in the spectral bandwidth of the pulse. For this example the bandwidth would be 20 MHz. Limiting the peak power to 0 dBm in a 20 MHz bandwidth would increase the peak power in the EESS sensor bandwidth to 0 dBm and the average power in the sensor bandwidth would be -16.8 dBm.

Pulsed FH Signal (No Overlap of Hop Channels)

For this analysis, the following pulsed FH system characteristics are considered:

Hopping frequency range - 1 GHz with hopping through out the 23.6 to 24 GHz band, Number of hop channels - 50, resulting in a 20 MHz spacing between hop channels;

PW - 50 nanoseconds, resulting in a pulse bandwidth of 20 MHz;

Hopping sequence - sampling without replacement to define the order for one cycle. This cycle is then repeated resulting in the return to each hopping channel on a regular periodic basis;

PRF - 1 MHz.

The duty cycle of the hopping waveform is:

$$DC = -10 \log (PRF \times PW) = 13 \text{ dB}$$

For an individual hopping channel, the duty cycle, because of the hopping sequence assumed, would be:

$$DC_h = -10 \log (PW \times PRF/\text{No. of channels}) = 30 \text{ dB}$$

If the peak power of a pulse is set to P_w, then the average power on a single hop channel would be:

$$A_{wh} = P_w - 30 \text{ dB}$$

with both P_w and A_{wh} referenced to a 20 MHz bandwidth When measured in a 1 MHz bandwidth, the peak power (P_m) would be.

$$P_m = P_w - 20 \log (20 \text{ MHz}/1 \text{ MHz}) = P_w - 26 \text{ dB}$$

The average power would be:

$$A_m = P_w - 30 \text{ dB} - 10 \log (20 \text{ MHz}/1 \text{ MHz}) = P_w - 43 \text{ dB}$$

Adjusting P_m for a 50 MHz bandwidth, results in:

$$P_{50} = P_w - 26\text{dB} + 20 \log (50 \text{ MHz}/1 \text{ MHz}) = P_w + 8 \text{ dB}$$

Comparing this to the measured average power of P_w - 43 dB and the frequency hopping signal will be peak power limited (according to the emission limits) not average power limited. Furthermore, the waveform pulse peak power is limited to -8 dBm to satisfy the constraint that the peak power referenced to 50 MHz (P_w + 8 dB) is limited to 0 dBm.

Thus, the peak power measured in a one MHz bandwidth would be:

$$P_m = -8 \text{ dBm} - 26 \text{ dB} = -34 \text{ dBm}$$

and the corresponding average power would be:

$$A_m = -8 \text{ dBm} - 43 \text{ dB} = -51 \text{ dBm}$$

With the EESS sensor receiver bandwidth of 400 MHz, the peak power out of the filter will be - 8 dBm as the receiver would see the complete (resolved) 20 MHz wide pulse. In the 400 MHz bandwidth, the EESS sensor receiver would see 20 hop channels (400/1000 x 50). The determination of the average power in the 400 MHz bandwidth requires first computing the effective duty cycle. The duty cycle of the complete waveform was previously shown to be - 10 log (PRF x PW) = 13 dB. However, in the 400 MHz bandwidth only an effective 20 out of 50 hopping channels will be seen. Thus, the PRF used in the waveform duty cycle determination must be reduced by the ratio of 20/50. This effective duty cycle is then:

$$DC_e = -10 \log (PRF \times 0.4 \times PW) = 16.9 \text{ dB}$$

and the average power is 16.9 dB below the peak power or - 8 dBm -16 9 dB = -24.9 dBm

Instead of defining the peak power in a 50 MHz bandwidth, the peak power can be defined in the spectral bandwidth of the pulse. For this example the bandwidth would be 20 MHz. Limiting the peak power to 0 dBm in a 20 MHz bandwidth would increase the peak power in the EESS sensor receiver bandwidth to 0 dBm and the average power in the sensor bandwidth would be -16.9 dBm.

Pulsed FH Signal (No Overlap of Hop Channels)

For this analysis, the following pulsed FH system characteristics are considered:

Hopping frequency range - 1 GHz with hopping through out the 23.6 to 24 GHz band;

Number of hop channels - 100, resulting in a 10 MHz spacing between hop channels;

PW - 0.2 microseconds, resulting in a pulse bandwidth of 5 MHz;

Hopping sequence - sampling without replacement to define the order for one cycle. This cycle is then repeated resulting in the return to each hopping channel on a regular periodic basis;

PRF - 1 MHz.

The duty cycle of the hopping waveform is:

$$DC = -10 \log (PRF \times PW) = 7 \text{ dB}$$

For an individual hopping channel, the duty cycle, because of the hopping sequence assumed, would be:

$$DC_h = -10 \log (PW \times PRF/\text{No. of channels}) = 27 \text{ dB}$$

If the peak power of a pulse is set to P_w, then the average power on a single hop channel would be.

$$A_{wh} = P_w - 27 \text{ dB}$$